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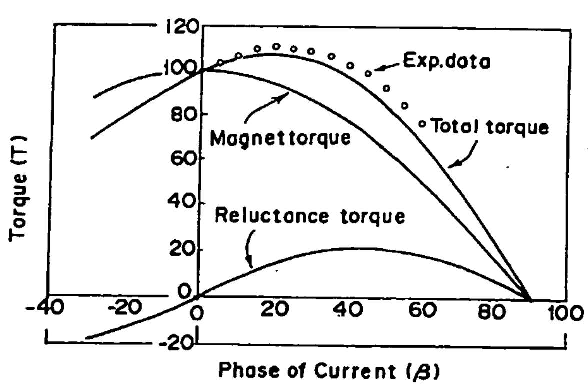
(54) Motor with built-in permanent magnets

(57) A rotor of a motor comprises a plurality of sets of permanent magnets 8a, 8b embedded in the rotor, and each set includes a permanent magnet at the inner side and another permanent magnet at the outer side with a distance between them. Each permanent magnet 8a, 8b is formed like an arch projecting towards the center of the rotor. Then, magnetic flux becomes easy to flow through an interval between the permanent magnets at the inner and outer sides, and the inductance in q-axis is enlarged. Then, the reluctance torque is generated in addition to the magnet torque, and the motor has a high torque and a high output power.

Fig. 3



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Description

BACKGROUND OF THE INVENTION

Field f the Invention

The present invention relates to a motor having permanent magnets built in a rotor thereof.

Description of the Prior Art

It is known that a magnetic motor has one-layer permanent magnets in a rotor made of a high permeability material such as iron. For example, in a prior art surface magnet motor, permanent magnets are attached to a surface of a rotor.

Recently, environmental issues have attracted intensive attention. In order to save energy, a motor with built-in permanent magnets, that is, with permanent magnets embedded inside a rotor has been noted to replace with the surface magnet motor.

Fig. 1 shows an example of a prior art motor with built-in permanent magnets. The motor comprises a rotor 3' and a stator 2. In the motor, each permanent magnet 17 having an form of arch projecting towards the center of the rotor 3' is embedded inside a rotor core 3a' made of an iron core of a high magnetic permeability material or of silicon steel sheets. The motor shown in Fig. 1 has four poles, and four permanent magnets 17 are arranged along a circumferential direction of the rotor to have N and S poles arranged alternately. The stator 2 has teeth 6.

In the above-mentioned motor, there is brought about a difference between an inductance Ld in a d-axis direction (refer to Fig. 1) connecting the center of each permanent magnet with the center of the rotor, and an inductance in a q-axis direction (refer to Fig. 1) rotated by 90° from the d-axis direction in terms of an electrical angle. Therefore, a reluctance torque is produced in addition to a magnet torque of the permanent magnets 17. A total torque T is expressed in Equation (1):

$$T = Pn^*\{\Psi a^*Iq + 1/2(Ld - Lq)^*Id^*Iq\}, \qquad (1)$$

wherein Pn denotes a number of pole pairs, Ψa denotes a magnetic flux in d-axis, Ld denotes an inductance in d-axis, Lq denotes an inductance in q-axis, Iq denotes a current in q-axis and Id denotes a current in d-axis. Equation (1) represents a voltage equation after the dq conversion. Magnet torque and reluctance torque are expressed in the first term and in the second term in a term expressed in parentheses { and } in Equation (1).

In the prior art surface magnet motor, since a magnetic permeability of the permanent magnet is approximately equal to that of the air, the inductances Ld and Lq have nearly the same value, and therefore no reluctance torque is generated.

In contrast, in the prior art motor with built-in permanent magnets, the d-axis direction corresponds to a direction in which a magnetic flux is generated by the permanent magnets 17, and as shown in Fig. 1, a flow 21 of magnetic flux in the d-axis direction penetrates twice the permanent magnet having approximately the same magnetic permeability as air, thereby the inductance Ld in d-axis is considerably reduced because of an increase in magnetic resistance. On the other hand, a flow 22 of magnetic flux in the q-axis direction is directed to a side face of the permanent magnet 17, passing the side face of the magnet as indicated in Fig. 1. As a result, the magnetic resistance is reduced and the q-axis inductance Lq is increased. The inductance Ld in d-axis becomes consequently different from the inductance Lq in q-axis. If a Id in d-axis current is supplied, the reluctance torque is generated.

Fig. 2 is a magnetic flux vector diagram illustrating this relation. The magnet torque is generated by multiplying a magnetic flux Ψa with a current Iq in a direction perpendicularly electrically to the magnetic flux. The magnetic flux Ψa is a component in d-axis of the total magnetic flux Ψ0. Similarly, the reluctance torque is generated by multiplying magnetic fluxes Ld*Id, Lq*Iq with currents Iq, Id flowing perpendicularly to the magnetic flux, respectively. A sum of these two torques becomes the total torque T.

The total torque T depends on a phase β of an input current I0, where $Iq = I0^*\cos\beta$ and $Id = I0^*\sin\beta$. Fig. 3 shows a relation of the magnet torque, reluctance torque and total torque when the current phase β is changed while the current value is kept at I0. The magnet torque is maximum when the current phase is 0°, and it becomes smaller as the phase β is increased, and it becomes zero when the phase is 90°. On the contrary, the reluctance torque has a maximum value when the current phase is 45°. Therefore, the total torque T becomes maximum in a range of 0 - 45° of the current phase. Marks o indicate values obtained in an experiment, and the values agree well with values calculated according to Equation (1). That is, with the same current, a larger torque is obtained in the motor having permanent magnets embedded in the rotor thereby to utilize the reluctance torque than in the surface magnet motor.

Next, a problem of the prior art motor having permanent magnets embedded in the rotor is explained. The reluctance torque is utilized to some extent in the motor. However, as indicated in Fig. 1, a flow 22 of the magnetic flux in the q-axis direction is obstructed by an end 17a of the permanent magnet 17 and cannot enter into the rotor. Most of the flow barely touches an outer peripheral part 18 of the permanent magnet 17. Thus, an amount of the magnetic flux is small, and the inductance Lq in q-axis cannot be increased.

As mentioned before, the larger is the difference between the inductances Lq and Ld (Ld is very small), the more is the reluctance torque generated by the same current. However, the q-axis inductance Lq cannot be increased so much in the prior art motor, and

therefore the difference of the inductances Lq and Ld cannot be made large.

SUMMARY OF THE INVENTION

An object of the present invention is to provide a motor with built-in permanent magnets which is highly efficient to generate a high output.

When the permanent magnets of the same amount in a motor with built-in permanent magnets are used, the d-axis inductance Ld is not greatly changed physically. However, the inventors notes that the q-axis inductance Lq may be increased if a design of the permanent magnets to be embedded is devised. In one aspect of the invention, a motor comprising a stator and a rotor comprising a rotor core embedding a plurality of sets of permanent magnets. A set of the permanent magnets comprises a plurality of permanent magnets, and the plurality of sets of permanent magnets are arranged to have N and S poles alternately at outer peripheral sides of the permanent magnets. The permanent magnets in a set extend so that ends thereof are positioned near an outer periphery of the rotor. Thus, a path is provided for a magnetic flux between the permanent magnets at the outer side and those at the inner side. This structure increases the q-axis inductance Lq as much as possible and enlarges a difference between the q-axis inductance Lq and the d-axis inductance Ld as much as possible, so that the reluctance torque produced with the same current is utilized to the utmost. A number of the permanent magnets in a set is for example two. Preferably, each of the permanent magnets has a shape of an arch projecting towards a center of the rotor. For example, an interval between two permanent magnets in a set of permanent magnets is constant.

In a second aspect of the motor of the invention, the interval between two-layer permanent magnets is wider at least at ends thereof at a leading side of a rotating direction of the rotor than at other parts thereof. In a different way, the interval is wider at ends of the permanent magnets than at other portions. Thus, the concentration of magnetic flus around the ends of the permanent magnet is eased.

In a third aspect of the invention, in the motor, both ends of each of the permanent magnets are tapered towards the ends thereof near an outer surface of the rotor and extending perpendicularly to the surface of the rotor. Then, magnetic flux flowing through a path between two permanent magnets can be enhanced.

In a fourth aspect of the rotor of the invention, the rotor embeds a set of the plurality of sets each comprising two permanent magnets in the rotor core. One of the two permanent magnets at an inner side of the rotor has a thickness larger by 3 % or more than that of the other of the two permanent magnets at an outer side of the rotor. In a different way, the permanent magnet at an inner side of the rotor is made of a magnetic material having a remanent magnetic flux density larger by 3 % or more than a magnetic material of the other of the two permanent magnets at an outer side of the rotor. Then, the magnetic flux of the permanent magnet at the backup side or at the inner side can be can be enhanced.

An advantage of the present invention is to provide a motor of a higher torque and a higher output power.

Another advantage of the present invention is to provide a motor having improved resistance against demagnetization.

BRIEF DESCRIPTION OF THE DRAWINGS

These and other objects and features of the present invention will become clear from the following description taken in conjunction with the preferred embodiments thereof with reference to the accompanying drawings, and in which:

Fig. 1 is a sectional view of a conventional motor with built-in permanent magnets of one layer;

Fig. 2 is a magnetic flux vector diagram after the d-q conversion;y

Fig. 3 is a graph showing a relation of a current phase, a magnet torque, a reluctance torque and a total torque;

Fig. 4 is a sectional view showing an embodiment of the present invention;

Fig. 5 is a partial enlarged view of Fig. 4;

Fig. 6 is a graph of a relation of a width of an interval between inner and outer permanent magnets and the q-axis inductance.

Fig. 7 is a diagram of an analysis of a flow of magnetic fluxes in a q-axis direction in the embodiment;

Fig. 8 is a diagram of an analysis of a flow of magnetic fluxes in a q-axis direction in the prior art motor;

Fig. 9 is a diagram of an analysis of the flow of the magnetic fluxes when a motor of the embodiment is rotated;

Fig. 10 is a diagram of an analysis of the flow of the magnetic flux when the prior art motor is rotated;

Fig. 11 is a graph of a relation of a generated torque plotted against a number of layers of magnets;

Fig. 12 is a graph of a relation a q-axis inductance plotted against of a number of layers of magnets;

Fig. 13 is a graph of a relation of a magnetic flux of magnets plotted against a number of layers of magnets;

Fig. 14 is a graph of a relation of a B-H curve of a permanent magnet to operating points of the magnet;

Fig. 15 is a schematic sectional view of a part of the motor of the first embodiment;

Fig. 16 is a diagram of an analysis result of magnetic flux by a permanent magnet.

Fig. 17 is a diagram of an analysis result of magnetic flux generated by windings;

Fig. 18 is a diagram of an analysis result of a synthetic magnetic flux produced by the permanent magnet and the windings;

Fig. 19 is a sectional view of a second embodiment of the present invention;

Fig. 20 is a partial sectional view of a third embodiment of the present invention;

Fig. 21 is a diagram for explaining the principle of the second embodiment;

Fig. 22 is a sectional view of a fourth embodiment of the present invention;

Fig. 23 is a graph of an H-B characteristic of permanent magnets;

Fig. 24 is a sectional view of the motor of the first embodiment;

Fig. 25 is a partial sectional view of Fig. 24;

Fig. 26 is a sectional view of a fifth embodiment of the present invention;

Fig. 27 is an enlarged sectional view of an essential part in Fig. 26; and

Fig. 28 is a graph of a relation of a passing amount of magnetic flux on Pa to Lm/Lt.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Referring now to the drawings, wherein like reference characters designate like or corresponding parts throughout the views, embodiments of the present invention will be explained in detail with reference to the drawings. Figs. 4 and 5 show a motor with built-in permanent magnets of four poles of a first embodiment. The motor comprises a rotor 3 adhered to a rotor shaft 7 and a stator 2 which houses the rotor 3. -

The rotor 3 comprises four sets of two-layer permanent magnets 8a, 8b embedded in a rotor core 3a made of a high magnetic permeability material. A set of the two-layer permanent magnets is composed of a permanent magnet 8a at an outer side and another permanent magnet 8b at an inner side, and the four sets of two-layer permanent magnets 8a and 8b are arranged to have N and S poles alternately at outer peripheral sides thereof. The inner and outer sides are defined with respect to a radial direction from the center of the rotor. In a different way of explanation, a permanent magnet for one pole is divided into two magnets 8a, 8b in a radial direction of the rotor 3. Each of the permanent magnets 8a and 8b is formed like an arch projecting towards the center of the rotor 3, while both ends 9a, 9a thereof are located near the outer periphery of the rotor 3. An interval M between the outer and inner permanent magnets 8a and 8b has an approximately constant width. In Fig. 4, d-axis direction is defined as a direction connecting the center of each permanent magnets 8a, 8b with the center of the rotor 3, while q-axis is defined as a direction connecting a boundary between adjacent poles with the center of the rotor 3. A path 10 of magnetic flux in q-axis direction is formed through the interval.

The stator 2 has a predetermined number of teeth 4, and stator windings 10 (not shown) are wound therebetween. When an alternating current is supplied to the stator windings, a rotational magnetic flux is generated. Thus a magnet torque and a reluctance torque to be exert on the rotor 3 are generated to rotate it.

It is desirable that the interval M between the outer and inner permanent magnets 8a and 8b is as small as possible in order to reduce a loss of a magnetomotive force at the permanent magnets 8a and 8b. However, it is also desirable that the interval is large enough not to be magnetically saturated in order to increase a q-axis inductance Lq. Therefore, in the present embodiment, the interval M is set to be about a half of a width N of the teeth 4 so that the magnetic flux generated by the current flowing in the stator windings is not saturated.

This is explained with experimental data shown in fig. 6 on the interval M and the q-axis inductance Lq. If the interval M is smaller than a third of the width N of the teeth 4, the q-axis inductance Lq becomes small rapidly. On the other hand, even if the interval M is larger than the width N of the teeth 4, the inductance Lq in q-axis is hardly changed. From this experimental data, it is preferable that the distance between the outer and inner permanent magnets 8a and 8b, namely, the interval M is larger than a third of the width N of the stator 2.

In order to enhance the magnetic flux as large as possible, the permanent magnet 8b at the inner side is constructed as large as possible within a polar pitch (90° if there are four poles as in this embodiment). On the other hand, a gap S (Fig. 5) between adjacent permanent magnets 8a and 8b is as small as possible to eliminate a leakage of the magnetic flux in order to effectively utilize the magnet torque. From a view point of cost, it is preferable to design the outer and inner permanent magnets 8a, 8b so that the amount of magnets for a pole is kept constant.

In the above-described structure, the path 10 where the magnetic flux in the q-axis direction flows is surely formed not to be saturated magnetically when the motor is driven. Therefore, the inductance Lq in q-axis can be increased to the utmost. At the same time, by using the amount of magnets approximately the same as in the prior art motor with one-layer built-in magnets, the d-axis inductance Ld is made as small as in the prior art motor. In other words, while the d-axis inductance Ld is not changed by using the same amount of magnets, the q-axis inductance Lq is increased by about 15 % or more (Fig. 11), so that the reluctance torque resulting from the difference between the q-axis inductance Lq and the d-axis inductance Ld can be utilized to the utmost. Then, the motor has an suitable structure for utilizing both the magnet torque and the reluctance torque to the utmost when the motor is driven with the same current.

In the embodiment described above, each of the permanent magnets 8a and 8b is formed in the arch-like shape projecting towards the center of the rotor. However, the permanent magnets may have other shapes,

e.g., concave U-shape projecting towards the center of the rotor. Although each permanent magnet 8a, 8b is all a permanent magnet up to the ends 9a, 9a in the embodiment, the ends 9a, 9a thereof may comprise air gap (air layer) or may be made of a layer filled with a synthetic resin.

Performance of the motor of the present embodiment is explained further. As explained above, in the motor of the first embodiment, a path of a magnetic flux is provided between the outer and inner permanent magnets. Then, a magnetic resistance is reduced to increase a q-axis inductance Lq remarkably. Accordingly, the reluctance torque is more effectively generated with the same current due to an increase in difference between the inductances Ld and Lq.

Figs. 7 and 8 show how easily magnetic flux in the q-axis direction flows in the motor of the present invention with embedded two-layer magnets and in the prior art motor with one-layer embedded magnets, respectively. As shown in Fig. 8, in the prior art motor using one permanent magnet in one pole, the magnets 17 are thick and therefore, the end 17a thereof obstructs a magnetic flux 11 generated by the stator windings from entering the rotor. On the other hand, as shown in Fig. 7, in the motor of the present embodiment having embedded two-layer magnets, because of the presence of the path 10 for the magnetic flux between the outer permanent magnet 8a and the inner permanent magnet 8b, the magnetic flux 11 generated by the stator windings is not obstructed by the permanent magnets, but passes through the path 10 smoothly to an exit 12 at the opposite side. In other words, this difference of the easiness of the magnetic flux flow between the prior art and the invention is proportional to a size of the q-axis inductance Lq, and the motor of the present embodiment facilitates efficient passing of magnetic flux to have a larger Lq.

Figs. 9 and 10 are diagrams of a flow of magnetic fluxes and an amount of the magnetic fluxes in the motor of the present invention and in the prior art motor, respectively, when the motor is actually rotated in K direction with the same amount of the current. It is found that the above-described difference in the inductance Lq makes it possible to generate more magnetic fluxes in the motor of the embodiment (Fig. 9) than in the prior art motor (Fig. 10). That is, a larger torque is generated due to the larger magnetic flux.

Fig. 11 shows experimental data on a relation of a generated torque to a number of layers of magnets. The torque of a motor of a rated output 750 W is measured with a constant current and a constant revolution number. As described before, the magnetic flux in the q-axis direction flows between the inner and outer permanent magnets in the two-layer structure. Then, the magnetic resistance is decreased more than in the prior art motor of one-layer magnets, resulting in the generation of a larger q-axis inductance Lq. Meanwhile, a d-axis inductance Ld is hardly changed because the same amount of magnets is used (and the d-axis inductance Ld is also very small). The difference between the q-axis inductance Lq and the d-axis inductance Ld is accordingly increased, and this increases the reluctance torque generated with the same current. Then, the total torque that is a sum of the reluctance torque and the magnet torque is increased approximately 15 %.

However, as shown in Fig. 11, if a number of layers of permanent magnet is increased further to three or four, the total torque is rather decreased.

Fig. 12 shows experimental data on a relation between a number of layers of magnets and the q-axis inductance Lq. The q-axis inductance Lq is increased about 50 % when the number of layers is changed from one to two. However, Lq is increased slightly when the number of layers of magnets is increased further to three or four, or the advantage is not so large as when the number is changed from one to two. This means that when the number of the permanent magnets are arranged in three or more layers, the q-axis inductance Lq is not changed largely as far as the path for the magnetic path in the q-axis direction formed between the permanent magnets divided in two layers is not magnetically saturated.

On the other hand, in an example shown in Fig. 13, the magnetic flux generated by the permanent magnets is highest when the permanent magnets are arranged in two layers, in contrast to other cases where the magnetic flux is smaller. In other words, when a number of layers of magnets is increased, the magnetic flux in the q-axis direction becomes easier to pass, so that the q-axis inductance Lq is increased. However, if the number of layers is three or more, each permanent magnet becomes thin and therefore, an operating point of the permanent magnets becomes lower, whereby an amount of generated magnetic flux is decreased. Then, as shown clearly in Fig. 11, the total torque determined by the addition of the magnet torque generated by magnetic flux of magnets and the reluctance torque generated by the difference between the q-axis inductance Lq and the d-axis inductance Ld becomes maximum when the number of division of magnets is two, and it is decreased when the number of layers is smaller than two or larger than two.

Equation (2) shows a calculation formula for a permeance factor P which determines the operating point of the magnet.

$$P = (Lm^*Ag^*Kf)/(Lg^*Am^*Kr), \qquad (2)$$

wherein Lm denotes a thickness of the magnet, Lg denotes a length of air gap, Am denotes a sectional area of the magnet, Ag denotes a sectional area of the air gap, Kf denotes a coefficient of a loss of magnetomotive force, and Kr is a leakage coefficient. The permeance factor P is proportional to the thickness Lm of the magnet and inversely proportional to the sectional area Am of the magnet if the length Lg of the air gap, the sectional area Ag of the air gap, the coefficient Kf of the

loss of the magnetomotive force and the coefficient Kr of the leak are kept the same. Fig. 14 shows a second quadrant of a B-H (magnetic flux density-magnetic field) curve of the permanent magnet. The operating point of the prior art one-layer magnet is determined by the magnetic flux density at a point B2. In the case of the two-layer magnets, the thickness Lm of the magnet is reduced, while the sectional area Am is increased, whereby an operating point B1 is not different from B2 or slightly increased. On the other hand, if the number of the magnets are three or more, the fact that the thickness Lm is decreased becomes more influential, and the operating point is lowered to a point B3.

To sum up, in the motor with embedded permanent magnets in the rotor in order to increase the difference between the q-axis inductance Lq and the d-axis inductance Ld for utilizing the reluctance torque, the structure where the two-layer permanent magnets per one pole are arranged is optimum for utilizing both the magnet torque and the reluctance torque represented in Equation (1) most efficiently. Further, the torque generated by the same current is enlarged, and the performance of the motor is improved to a large extent.

Further, when the permanent magnets are arranged in two layers as in the present embodiment, the magnetic flux passing through the tooth 4 of the stator 2 to the rotor 3 is smoothly guided along the path 10 formed between the inner and outer permanent magnets 8a, 8b to other teeth 4. Then, the permanent magnets 8a, 8b are prevented from being demagnetized, or it improves the resistances of demagnetization of the permanent magnets. On the contrary, the prior art surface magnet motor or in the prior art motor with built-in magnets of one layer have problems of demagnetization. That is, the magnetic flux in the q-axis direction flowing from the teeth 4 to the rotor 3 tends to exert on the permanent magnets, thereby subjecting the permanent magnets to demagnetization.

Next, second and third embodiments of the invention are explained. In the motor of the first embodiment, as shown in Fig. 15, the interval 3b between the permanent magnets 8a and 8b are constant. Then, it is a problem that a magnetic flux synthesized from a magnetic flux generated by the permanent magnets 8a, 8b embedded in the rotor core 3a and a magnetic flux produced by the windings of the stator 2 tends to concentrate at the interval or gap 3b at the ends 9a, 9b of permanent magnets 8a, 8b at the leading side of a rotating direction R of the rotor 3. This is explained with reference to Figs. 16 - 18. Fig. 16 shows an analysis of magnetic flux formed only by permanent magnets 1, 2. Fig. 17 shows magnetic flux generated by the windings 10 of the stator 2, in which permanent magnets are regarded as magnetic voids 8c. Fig. 18 shows synthetic magnetic flux by the permanent magnets 8 and windings 10. Lines of magnetic force are densely concentrated at each interval 3b of ends 9a, 9b of permanent magnets 8a, 8b located at the leading side of the rotor 3 rotating in the R direction shown in Figs. 15 - 18. A blank denoted by 5 in Fig. 18 shows a space between the teeth 4. The concentration of magnetic flux at the intervals 3b induces an increase in core loss, causing the rotor core 3a to generate heat and eventually deteriorating the efficiency of the motor.

Further, in the motor of the first embodiment, two layers of the permanent magnets 8a and 8b are spaced generally in parallel to each other. Therefore, amounts of magnetic fluxes of two permanent magnets 8a, 8b at the surface of the rotor 3 is determined solely by a surface area of an outer peripheral side of the permanent magnet 8a at the outer side in the rotor core 3a, that is, a magnet torque at both ends 9b of the permanent magnet 8b located inside the permanent magnet 8a is not fully utilized.

Under the circumstances, it is desirable to lessen the concentration of the magnetic flux generated at the interval 3b between the ends of the two permanent magnets at the leading side of the rotating direction R and improve the efficiency of the motor.

In the second embodiment of the present invention, in order to solve the problems, a rotor with permanent magnets is designed to lessen the concentration of magnetic flux at specified positions, while utilizing both a magnet torque and a reluctance torque efficiently. Fig. 19 represents motor of the second embodiment of the present invention. The motor comprises a rotor 3 adhered to a rotor shaft 7 and a stator 2 which houses the rotor 3. The rotor 3 comprises four sets of permanent magnets 8a, 8b embedded in an iron rotor core 3a thereof. The permanent magnets 8a, 8b in each set for a pole are spaced with a distance 3b between them in a radial direction of the rotor 3. The permanent magnets 8a, 8b of each set are adjacent to each other with S and N poles arranged alternately. Moreover, the two-layer permanent magnets 8a, 8b in each set show the same polarity at outer peripheries thereof. All of the permanent magnets 8a at the outer side and the permanent magnets 8b at the inner side of the rotor have shapes of arc in a centripetal direction of the rotor, as in the first embodiment.

The interval 3b between ends 9a, 9b of the permanent magnets 8a and 8b in each set at the leading side of rotating direction R of the rotor 3 has a width w wider than at other parts, while the interval at the other ends of the permanent magnets has a smaller with x.

Meanwhile, the stator 2 has a plurality of teeth 4, with windings 10 provided in the teeth 4. A rotational magnetic field is generated when a current is supplied to the windings 10.

In the above-described motor, the rotor 3 has the main body 3a coated with iron which is highly magnetically permeable and therefore easy to pass a magnetic flux when receiving the rotational magnetic field from the windings 10, and permanent magnets 8 (8a, 8b) of a low magnetic permeability not allowing the magnetic flux to pass easily. At the same time, the rotor 3 is so adapted as to show an inductance in a direction of d-axis which is the radial direction passing the centers of

the permanent magnets 8 of each set, different from an inductance in a direction of q-axis in which an electrical angle intersects at right angles to the d-axis direction, as shown in Fig. 19.

In the motor, the magnetic flux generated by the windings 10 is not allowed to pass in the d-axis direction of Fig. 19 thereby to remarkably reduce the inductance. On the other hand, a magnetic path is generated at the interval of the inner and outer permanent magnets 8b and 8a in the q-axis direction having the electrical angle orthogonal to the d-axis direction. Thus, the magnetic flux is facilitated to pass to increase the inductance, or a reluctance torque is effectively utilized. A magnetic path is formed also in Pa direction shown in Fig. 19.

In the first embodiment shown in Fig. 4, when the rotor 3 is rotated in the R direction, the magnetic flux is concentrated and easily saturated at the interval 3b (having the width x) at the ends 9a and 9b of the permanent magnets 8a and 8b at the leading side in the rotating direction R. On the contrary, according to the present embodiment, because the interval 3b between the ends 9a and 9b of the permanent magnets 8a and 8b at the leading side in the rotating direction R is set wide, as indicated by W in Fig. 19, the concentration of magnetic flux at the interval 3b is lessened.

In the present embodiment, a rotating position and a revolution number of the rotor 3 are detected beforehand by a Hall device or an encoder. In order to generate a large reluctance torque and a large magnet torque, an alternating current of a frequency corresponding to the revolution number of the rotor 3 and with a shifted phase is supplied to the windings 10 of the stator 2, so that the current has a peak at a position slightly shifted in phase from the q-axis.

In the above-described motor according to the second embodiment, it is advantageous that the magnetic flux generated at the interval at the leading side of the rotor rotating in the widened direction can be prevented from being concentrated so much, as described above. Further, when each of the permanent magnets embedded in two layers has a shape of an arc projecting towards the center of the rotor, the magnetic flux related to a reluctance torque is smoothly guided between the permanent magnets along the projecting arc. Thus, the magnetic resistance related to the formation of a magnetic path is reduced, thereby improving the efficiency of the motor.

Next, a third embodiment of the invention is described with reference to Figs. 20 and 21. As shown in Fig. 20 schematically, in the third embodiment, a center Rb of a curvature of the permanent magnet 8b at the inner side in the two layers is set to be farther from the center of the rotor 3 than a center Ra of a curvature of the permanent magnet 8a at the outer side. Thus, each of the intervals 3b between the ends 9a, 9b of permanent magnets 8a, 8b is formed wide. Except this point, the structure of the second embodiment is common to that of the second embodiment, and the common parts in the motor shown in Fig. 20 are designated by the same reference numerals, and the description thereon will be omitted here.

In the third embodiment, each interval 3b between ends 9a, 9b of the permanent magnets 8a and 8b at the leading side of the rotation direction R is kept as wide as W, or the interval at the leading side of the rotor is wide at all times, irrespective of the rotating direction of the rotor 3, i.e., whether the rotor 3 is rotated forward or backward. The concentration of magnetic flux at the interval 3b is accordingly lessened, as in the second embodiment. Then, a core loss is reduced.

As shown in Fig. 21, the inner permanent magnet 8b can increase magnetic flux further by parts 9c, 9d indicated by hatched lines in the drawing (refer (a) in Fig. 21). In other words, as shown in (b) schematically in Fig. 21, a magnetic flux N generated by the permanent magnet 8a at the side face is backed up by a magnetic flux N formed at a central part of the permanent magnet 8b arranged at the rear side of the above permanent magnet 8a and having the same surface area as the permanent magnet 8a. Meanwhile, as shown in (c), magnetic flux generated at both ends 9c, 9d of the permanent magnet 8b directly reach the surface of the rotor 3. Thus, besides the surface area of the permanent magnet 8a at the outer side, the surface area at both ends of the permanent magnet 8b at the inner side are added to be used effectively magnetically. Accordingly, a sum of magnetic flux due to the permanent magnet 8a and magnetic flux by the ends 9c, 9d is output to the surface of the rotor 3. Therefore, because the effective surface area of the permanent magnets 8 is increased, an amount of magnetic flux is increased efficiently so that a stronger magnet torque is generated.

In the second and third embodiments, four sets of permanent magnets 8a, 8b are employed, but a number of the sets may be different from four. Moreover, the shape of the permanent magnet 8 is not restricted to the arc projecting towards the center of the rotor. Although each of the permanent magnets 8a, 8b is totally made of a permanent magnet up to the ends 9a, 9b, the ends 9a, 9b thereof may be air gap (air layer) or be made of a synthetic resin layer. That is, these embodiments may be modified in various ways based on the spirit thereof which should not be excluded from the scope of the invention.

Next, fourth and fifth embodiments of the invention are explained which solve a further problem of the motor of the first embodiment which is explained below. In the motor of the first embodiment, the interval is provided between the permanent magnets 8a and 8b for the magnetic flux to pass therethrough in order to effectively utilize the reluctance torque. Then, as shown in Fig. 16, the magnetic flux coming out from both ends of the permanent magnet 8b at the inner side directly flows to the stator 2, without entering the permanent magnet 8a at the outer side, that is, without backing up the ends of the permanent magnet 8a at the outer side. Then, the outer permanent magnet 8a is backed up less by the inner permanent magnet 8b as a whole. An amount of

magnetic flux contributing to the magnet torque at the permanent magnet 8a at the outer side is consequently decreased, thereby reducing the total magnet torque.

Then, a motor of the fourth embodiments of the present invention will be described in detail. Fig. 22 is a sectional view of the motor of the fourth embodiment of the present invention. The motor comprises a rotor 3 adhered to a rotor shaft 7 and a stator 2 which houses the rotor 3. The rotor 3 has four sets of permanent magnets 8a and 8b embedded in a rotor core 3a made of iron. Each set of the permanent magnets 8a, 8b for a pole is formed in two layers with an interval between them in a radial direction of the rotor. The sets of the permanent magnets 8a, 8b are set to be adjacent to each other so as to have S and N poles arranged alternately. Moreover, the two-layer permanent magnets 8a, 8b in each set have the same polarity at outer peripheries thereof. Both outer and inner permanent magnets 8a, 8b are formed like an arch projecting towards the center of the rotor 3. The outer and inner permanent magnets 8a, 8b arranged in the two-layer structure are parallel to each other with a constant distance between them. It is to be noted that the inner permanent magnet 8b has a thickness Wb, as shown in Fig. 22, in the radial direction of the rotor 3, while the outer permanent magnet 8a has a thickness Wa which is smaller by 5 % than Wb.

On the other hand, The stator 2 comprises a plurality of teeth 4. Windings 10 are disposed between the teeth 4. A rotational magnetic field is generated by supplying an alternating current to the windings 10.

Fig. 23 is a diagram of an H (magnetic field)-B (magnetic flux density) characteristic, where the ordinate represents the magnetic flux density B and the abscissa represents the magnetic field H. The permanent magnets 8a, 8b are made of neodymium iron magnet which has a demagnetization curve 11 shown in Fig. 23. An operating point K1 of the outer permanent magnet 8a lies on a line connecting a remanent magnetic flux density B_r with a coercive force H_c. Since the inner permanent magnet 8b is thicker than the outer permanent magnet 8a, an operating point of the inner permanent magnet 8b is raised to a higher position K2.

A difference P between K1 and K2 in Fig. 23 represents a difference in magnetic flux density B. In the fourth embodiment, K2 is larger by nearly 4 % than K1.

As described above, because the magnetic flux density is increased by approximately 4 % at the inner permanent magnet 8b than at the outer permanent magnet 8a, a sufficient amount of magnetic flux is supplied to the outer permanent magnet 8a, thereby backing up the outer permanent magnet 8a enough, even if a part of the magnetic flux leaks out.

As descried above, in the motor according to the fourth embodiment, each permanent magnet is formed as an arch projecting towards the center of the rotor and the thickness of the permanent magnets at the inner side of the rotor of the two-layer permanent magnets is made larger by 3% or more than that of the permanent magnets at the outer side of the rotor. Then, the difference in thickness contributes to raise an operating point determining a magnetic flux density of the permanent magnets at the backup side. Accordingly, in comparison with the motor of the first embodiment, the magnetic flux density due to the permanent magnets at the inner side can be increased. Because the permanent magnets at the inner side fully back up even at the two ends of the permanent magnets 8a, 8b at the outer side, the problem of the first embodiment is solved. Then, the rotor with permanent magnets provided by the present embodiment thus effectively utilizes the magnet torque. However, if the thickness of the permanent magnets at the inner peripheral side is increased, but smaller than 3% than that of the permanent magnets at the outer side, the backup effect is not sufficient.

A fifth embodiment of the present invention will be described below. Inner and outer permanent magnets 8b, 8a are formed to have the same thickness in the present embodiment. This embodiment is the same as the fourth embodiment shown in Fig. 19 so long as the shape is concerned. However, this embodiment has a feature that the outer permanent magnets 8a are made of ferrite magnet, while the inner permanent magnets 8b are made of neodymium iron magnets.

In Fig. 23, reference numerals 11 and 12 represent H (magnetic flux)-B (magnetic flux density) characteristics of the neodymium iron magnet (permanent magnet 8b) and the ferrite magnet (permanent magnet 8a), respectively. As is clear from Fig. 23, a remanent magnetic flux density Br of the neodymium iron magnet 11 is approximately three times a remanent magnetic flux density Br' of the ferrite magnet 12. The outer permanent magnet 8a has a magnetic flux density determined by an operating point K3 in Fig. 23 and the inner permanent magnet 8b has a magnetic flux density determined by the operating point K1 in Fig. 23.

A difference Q between K1 and K3 represents a difference in magnetic flux densities of the inner and outer permanent magnets 8b, 8a. The inner permanent magnet 8b has the density nearly twice or more larger than that of the outer permanent magnet 8a.

Accordingly, even when the inner and outer permanent magnets 8b, 8a have the same thickness, if the permanent magnet made of a material of a larger remanent magnetic flux density B_r is arranged at the backup side (inner side), the outer permanent magnet 8a can fully be backed up, similar to in the fourth embodiment.

As described above, in the motor of the fifth embodiment of the present invention, the permanent magnets of the two-layer structure are made of magnetic materials of remanent magnetic flux densities different by 3% or more from each other and the permanent magnets of a larger remanent magnetic flux density are arranged at the backup side (inner side). Then, the magnetic flux density due to the permanent magnets at the backup side can be increased if compared with the motor of the first embodiment, similarly in the fourth embodiment. Then, the rotor with permanent magnets provided by

the present embodiment thus effectively utilizes the magnet torque.

However, if the remanent magnetic flux density of the permanent magnets at the inner side is increased, but smaller than 3% of the permanent magnets at the outer side, the backup effect is not sufficient.

Although four poles of permanent magnets 8 are used in the fourth and fifth embodiments, a number of poles may be other than four. Although the ferrite magnet 12 and neodymium iron magnet 11 are used as magnetic materials of different remanent magnetic flux densities in the fifth embodiment, other kinds of combinations, e.g., cobalt magnets and Alnico magnets may be used. Further, magnets of the same series, but having different remanent magnetic flux densities may be combined. Moreover, while each of the permanent magnets 8a and 8b in the fourth and fifth embodiments are totally made of a permanent magnet up to the ends thereof, the ends may be an air gap (air layer) or made of a synthetic resin layer. Further, features of the fourth and fifth embodiments may be combined. In other words, the present invention is not limited to the fourth and fifth embodiments and may be modified in various ways according to the spirit thereof which should not be excluded from the scope of the invention.

Next, a sixth embodiment according to the invention is explained. First, a problem to be solved by the sixth embodiment is explained. Fig. 24 shows the motor of the first embodiment where a rotor has two-layer permanent magnets in order to effectively utilize a reluctance torque. According to the first embodiment, four sets of two-layer permanent magnets 8a and 8b with a space between them in a radial direction of a rotor 3 are embedded in a rotor core 3a. The permanent magnets 8a, 8b in each set are adjacent to each other with S and N poles arranged alternately. Moreover, the permanent magnets 8a, 8b in a set have the same polarity at outer peripheral sides thereof. Every permanent magnet 8a, 8b at the inner and outer sides in the rotor is formed like an arch projecting towards the center of the rotor.

The outer and inner permanent magnets 8a and 8b are arranged to form concentric circles, keeping a constant distance therebetween. Because the two-layer permanent magnets 8a, 8b have shapes of arches projecting towards the center of the rotor, side faces of ends 9a, 9b thereof are rendered approximately orthogonal to the surface of the rotor.

As shown in Fig. 24 and 25, each permanent magnet 8a, 8b has the same width all over the length thereof, and a front end face 15a 15b of the permanent magnets is flat. Further, the inner permanent magnets 8b, 8b adjacent to each other become closest at points 16, 16 with a distance g, before reaching to the front end faces 15b, 15b, and it is opened like a fan at the front ends.

The rotor 3 of the motor of the first embodiment is rotated in R direction by a synthetic torque including a magnet torque and a reluctance torque. The magnetic torque results from a rotational magnetic field generated by windings 10 in teeth 4 of a stator 2 and a magnetic field by the permanent magnets 8a, 8b, while the reluctance torque is generated with a magnetic path of the above rotational magnetic field formed at the surface of the rotor core 3a and at the interval of the inner and outer permanent magnets 8b and 8a.

In the above-mentioned motor of the first embodiment, the most effective magnetic flux to obtain the reluctance torque is one formed along a magnetic path Pa shown in Fig. 3. In other words, among the magnetic flux flowing from one tooth 4 to the other tooth 4, the higher is the density of a magnetic flux passing the rear face of the outer permanent magnet 8a, the more is generated the reluctance torque.

However, the end faces 15a, 15b of the permanent magnets 8a, 8b forming a magnetic space are opposed to the teeth 4 with a considerable distance between them when the rotor 3 is at a rotating position shown in Fig. 25. As a result, the magnetic path Pa is excessively bent at this position, and a magnetic resistance at the magnetic path Pa is eventually increased. Then, the magnetic flux density at the magnetic path Pa is lowered considerably, making it impossible to generate the reluctance torque sufficiently.

Further, in the motor of the first embodiment, the points 16, 16 where the permanent magnets 8b at the inner side adjacent to each other become closest are located considerably inside from the outer periphery of the rotor 3. An amount of magnetic flux passing the interval of the permanent magnets is restricted by the distance g of the points 16, 16, and the fan-like part at the outer side than the points 16, 16 becomes a dead space 7. The presence of the dead space 7 is not preferable from a view point of efficient generation of the magnet torque and the reluctance torque.

The sixth embodiment of the present invention which solve the problem will be fully described below. Fig. 26 shows a motor 3 of the sixth embodiment. The motor comprises a rotor 3 adhered to a rotor shaft 7 and a stator 2 which houses the rotor 3. The rotor 3 comprises four sets of two-layer permanent magnets 8a and 8b for a pole with a space between them in a radial direction of the rotor 3. The four sets of permanent magnets are embedded in a rotor core 3a of the rotor 3 with a constant distance in a circumferential direction of the rotor 3. The four sets of the permanent magnets 8a, 8b are adjacent to each other with N and S poles arranged alternately. Moreover, the permanent magnets 8a, 8b in a set have the same polarity at outer peripheral sides thereof. The outer and inner permanent magnets 8a, 8b are formed like an arch projecting towards the center of the rotor. The outer and inner permanent magnets 8a, 8b in a set are arranged in parallel with a nearly constant distance between them except at ends 9a, 9b thereof.

The ends 9a, 9b of the permanent magnets 8a, 8b are tapered around the ends to be thinned towards the outer surface of the rotor 3. They are approximately perpendicular to the surface of the rotor 3. The end 9a of

the outer permanent magnet 8a is cut at both sides thereof to have a narrowed top end. On the other hand, the end 9b of the inner permanent magnet 8b is so formed that outer surfaces of the permanent magnet 8b and the other permanent magnet 8b at the inner side adjacent to the former permanent magnet extend in parallel to each other in the radial direction of the rotor 3 with a constant distance g between them (refer to Fig. 27). Moreover, the end 9b of the permanent magnet 8b at the inner side is cut to be narrowed only at a side of an inner surface thereof. Fig. 27 shows the cut-off part 17.

Because the ends 9a, 9b are narrowed as described above, front ends of the permanent magnets 8b, 8a at the inner side and at the outer side can be extended to positions in the vicinity of the surface of the rotor 3, without decreasing a strength of the rotor core 3a.

A plurality of teeth 4 are provided in a stator 2, with windings 10 wound therebetween. A rotational magnetic field is generated when an alternating current is supplied to the windings 10. The rotor 3 is rotated in R direction of Fig. 26 due to the rotational magnetic field. In Fig. 26, a flow path of the most effective magnetic flux to generate a reluctance torque is indicated as Pa.

In the present embodiment, as shown in Fig. 27, relations,

$$Lm1 = 0.4{*}Lt,$$

and

$$Lm2 = 0.4{*}Lt,$$

are satisfied, where Lt denotes a width between front ends of teeth 4 is, Lm1 denotes a width of the front end of the outer permanent magnet 8a, and Lm2 denotes a width of the front end of the inner permanent magnet 8b. The widths Lm1, Lm2 of front ends of the two permanent magnets 8a, 8b are preferably not to be larger than 0.7*Lt.

Fig. 28 shows a relation of a ratio Lm/Lt of the width Lm (= Lm1 = Lm2) of the front end of the permanent magnets 8a, 8b and the width Lt of front ends of the teeth 4, and an amount of magnetic flux flowing in the magnetic path Pa. If Lm/Lt is not larger than 0.7, the amount of magnetic flux becomes a predetermined value or higher, and it is stable.

According to the embodiment, a relation,

$$Ls = 1.5{*}Lk,$$

is satisfied where Lk denotes a pitch between front ends of the inner and outer permanent magnets 8a, 8b and Ls denotes a pitch of the teeth 4, as in Fig. 2. It is preferable that the pitches Lk, Ls hold a relation expressed by Equation (2) or (3);

$$1.3{*}Ls \leqq Lk \leqq 1.7{*}Ls, \qquad (2)$$

or

$$1.3{*}Lk \leqq Ls \leqq 1.7{*}Lk, \qquad (3)$$

where Lk denotes a pitch of front ends of the permanent magnet at the inner peripheral side of the rotor and the permanent magnet at an outer peripheral side of the rotor and Ls denotes a pitch of the teeth of the stator. It is also preferable that front end faces 15a, 15b of permanent magnets 8a, 8b do not agree with the front ends of the teeth 4 simultaneously.

Although four sets of permanent magnets 8a, 8b are employed in the sixth embodiment, a different number of sets may be allowed. Furthermore, although each permanent magnet 8a, 8b in the sixth embodiment is totally made of a permanent magnet up to the ends 9a, 9b, the ends 9a, 9b may be air space (air layer) or is made of a synthetic resin layer. Moreover, the permanent magnet 8 is not restricted to the two-layer structure, but may be formed in one layer or in three or more layers. While the pitch of front ends of the inner and outer permanent magnets 8a, 8b is set to hold Ls = 1.5, a different pitch from that of the embodiment may be adopted, e.g., satisfying Ls = Lk as in the first embodiment shown in Fig. 24. Although front ends of the permanent magnets 8a, 8b are cut off at side faces thereof to be narrowed in the motor of the present embodiment, the front ends may be rounded like an arch. In other words, the present invention is not limited to the above embodiment, but may be modified in various forms based on the aim thereof which should not be excluded from the scope of the invention.

The advantages of the present embodiment are explained here further. Because both front ends of each permanent magnet 8a, 8b are narrowed at positions near the surface of the rotor 3 and embedded approximately at right angles to the surface of the rotor 3, a magnetic flux density of a magnetic path Pa which effectively generates a reluctance torque is maintained high even when the rotor 3 is rotated to the rotating position as shown in Fig. 25. That is, because the opposed face of the permanent magnet 8a, 8b is narrowed at the front end thereof, the magnetic flux flowing on the magnetic path Pa is guided smoothly into the rotor 3 even when the teeth 4 of the stator 2 are at positions opposed to the end of the permanent magnet 8a, 8b. Therefore, the reluctance torque is effectively generated if compared with the first embodiment.

Because the width Lm of the narrowed front end of the permanent magnet 8a, 8b is not larger than 70% of the width Lt of front ends of the teeth 4 of the stator, more magnetic flux is guided to the magnetic path Pa, so that the above operation can be performed more effectively (refer to Fig. 28).

When the permanent magnets 8a, 8b are embedded in two layers for a pole with a distance between them in the radial direction of the rotor 3, and both ends of each permanent magnet 8a, 8b at the inner side of the rotor 3 are cut mainly at inner surfaces thereof to be

narrowed, much more magnetic fluxes are guided between the inner and outer permanent magnets 8a, 8b, thereby increasing the magnetic flux density on the magnetic path Pa acting effectively to the generation of the reluctance torque. A large amount of reluctance torque is accordingly obtained.

In the two-layer structure, if the pitch Lk at the front end parts of the inner and outer permanent magnets 8a, 8b is 1.3 - 1.7 times the pitch Ls of teeth 4 as represented in Equation (2), or if the Ls is set to be 1.3 - 1.7 times Lk, thereby not to make front end faces of both permanent magnets agree with the front end faces of the teeth 4 at the same time, the magnetic flux from the teeth 4 can be smoothly guided between the inner and outer permanent magnets 8a, 8b, so that a large reluctance torque is generated.

If outer surfaces at both ends of the adjacent permanent magnets are extended approximately parallel to each other in the radial direction of the rotor 3, the interval of the ends of the permanent magnet and the other permanent magnet adjacent to the above permanent magnet is rendered constant, thus eliminating a dead space. If the interval of both ends is set to be small, similar to the minimum distance g in the first embodiment, a surface area effective to generate a magnet torque of permanent magnets is expanded. Alternatively, if the interval at both ends is set to be larger than the minimum distance g, an amount of magnetic flux flowing in the interval is increased, so that reluctance torque generated is increased.

According to the present embodiment, even when the rotor is at a rotating position hard to utilize the reluctance torque in the first embodiment invention, the flow of magnetic fluxes is formed inside the rotor to facilitate the generation of the reluctance torque. Thus, the embodiment provides a rotor with permanent magnets effectively utilizing the reluctance torque.

Although the present invention has been fully described in connection with the preferred embodiments thereof with reference to the accompanying drawings, it is to be noted that various changes and modifications are apparent to those skilled in the art. Such changes and modifications are to be understood as included within the scope of the present invention as defined by the appended claims unless they depart therefrom.

Claims

1. A motor comprising:

   a stator having a plurality of windings wound around an iron core, and

   a rotor comprising a rotor core and surrounded by the stator rotatably;

   wherein the rotor comprises a plurality of sets of permanent magnets embedded in the rotor core, a set of the permanent magnets comprises a plurality of permanent magnets, the plurality of sets of permanent magnets are arranged to have N and S poles alternately at outer peripheral sides of the permanent magnets, the permanent magnets in a set extend so that ends thereof are positioned near an outer periphery of the rotor.

2. The motor according to claim 1, wherein each of the permanent magnets has a shape projecting towards a center of the rotor.

3. The motor according to claim 2, wherein the shape of each of the permanent magnets is an arch projecting towards a center of the rotor.

4. The motor according to claim 1, wherein an interval between two permanent magnets in a set of permanent magnets is constant.

5. The motor according to claim 4, wherein the stator comprises a plurality of teeth for forming windings, and the interval between the first and second permanent magnets is larger than a third of a width of the teeth.

6. The motor according to claim 1, wherein an interval between two permanent magnets in a set of permanent magnets is wider at least at ends thereof at a leading side of a rotating direction of the rotor than at other parts thereof.

7. The rotor according to claim 1, wherein a center of a curvature of a permanent magnet at an inner side in a set of permanent magnets is positioned farther from a center of the rotor than that of another permanent magnet at an outer side, so that an interval between the two permanent magnets is wider at ends of the permanent magnets than at other portions.

8. The motor according to claim 1, wherein both ends of each of the permanent magnets are tapered towards the ends thereof near an outer surface of the rotor and extending perpendicularly to the surface of the rotor.

9. The motor according to claim 8, wherein the stator comprises a plurality of teeth for windings, and a following relation is satisfied:

   $$Lm \leq 0.7^{*}Lt,$$

   where Lm denotes a width of the tapered end of the permanent magnet and Lt denotes a width between ends near the rotor of two teeth of the stator.

10. The motor with permanent magnets according to claim 8, wherein outer surfaces at the ends of adjacent permanent magnets of different polarities are extended in parallel to each other in the radial direction of the rotor.

11. The motor with permanent magnets according to claim 1, wherein a number of the sets of permanent magnets is four.

12. The motor with permanent magnets according to claim 1, wherein an end of the permanent magnets comprises a space filled with air of a synthetic resin.

13. A motor comprising:

a stator having a plurality of windings wound around an iron core, and

a rotor enclosed in the rotor;

wherein the rotor comprises a plurality of sets of two-layer permanent magnets embedded in a rotor core made of a high magnetic permeability material, a set of the two-layer permanent magnets comprises a first permanent magnet at an outer side and a second permanent magnet at an inner side of the rotor, the plurality of sets of two-layer permanent magnets are arranged to have N and S poles alternately at outer peripheral sides of the permanent magnets, the first and second permanent magnets extend so that ends thereof are positioned near an outer periphery of the rotor.

14. The motor according to claim 13, wherein each of the first and second permanent magnets has a shape of an arch projecting towards a center of the rotor.

15. The rotor according to claim 13, wherein a set of the plurality of sets comprises two permanent magnets embedded in the rotor core, each of the permanent magnets having a shape of an arch projecting towards a center of the rotor, and one of the two permanent magnets at an inner side of the rotor has a thickness larger by 3 % or more than that of the other of the two permanent magnets at an outer side of the rotor.

16. The rotor according to claim 13, wherein a set of the plurality of sets comprises two permanent magnets embedded in the rotor core, each of the permanent magnets having a shape of an arch projecting towards a center of the rotor, and a permanent magnet in the two permanent magnets at an inner side of the rotor is made of a magnetic material having a remanent magnetic flux density larger by 3 % or more than a magnetic material of the other of the two permanent magnets at an outer side of the rotor.

17. The motor according to claim 13, wherein both ends of the permanent magnet at an inner side of the rotor are cut at inner surfaces thereof to be tapered.

18. The motor according to claim 13, wherein the stator comprises a plurality of teeth for windings, and one of the following relations is satisfied:

$$1.3^{*}Ls \leqq Lk \leqq 1.7^{*}Ls,$$

or

$$1.3^{*}Lk \leqq Ls \leqq 1.7^{*}Lk,$$

where Lk denotes a pitch of adjacent ends of the two permanent magnets and Ls denotes a pitch of the teeth of the stator.

19. The motor with permanent magnets according to claim 17, wherein outer surfaces at the ends of adjacent permanent magnets of different polarities are extended in parallel to each other in the radial direction of the rotor.

Fig. 1

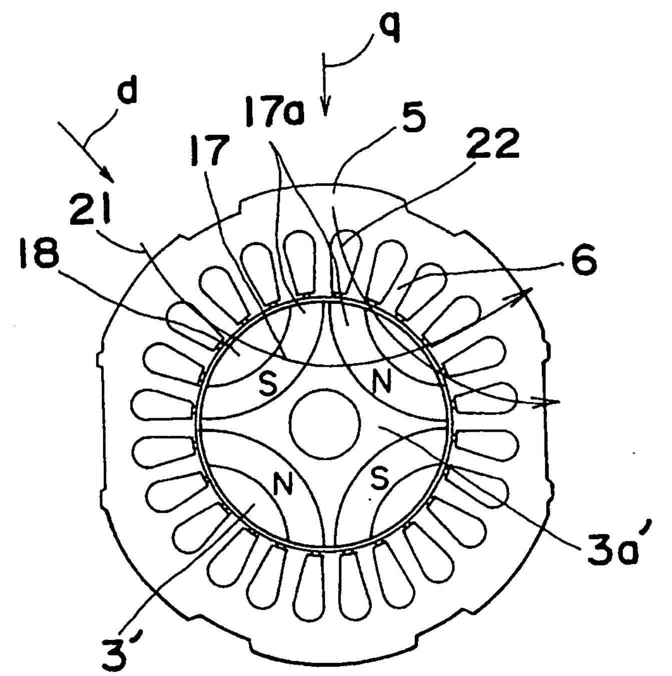
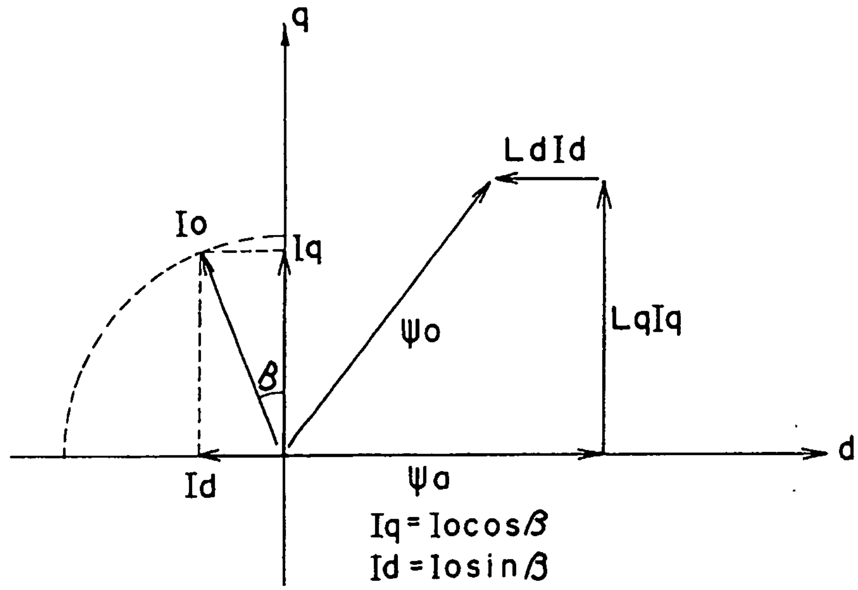
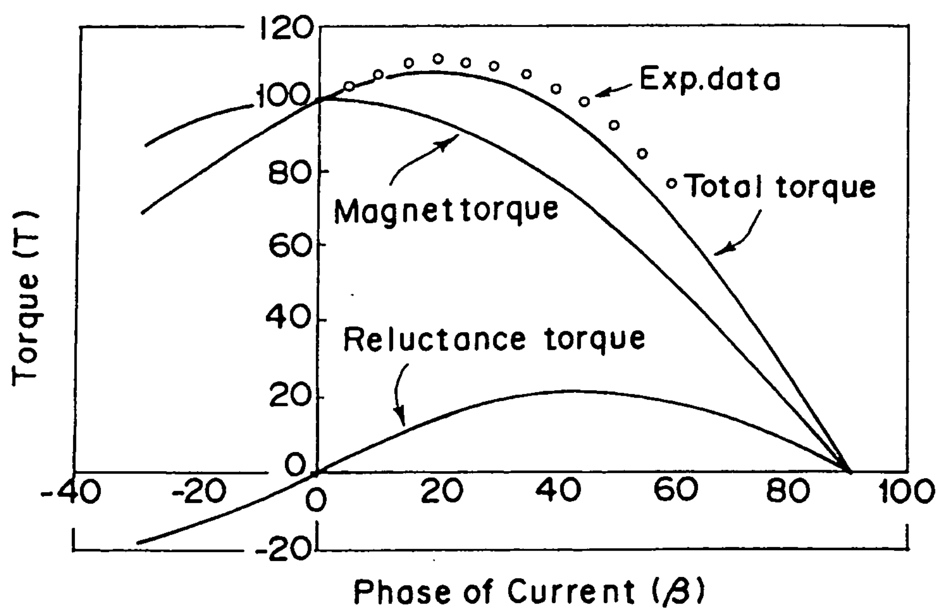


Fig. 2



q
LdId
Io
Iq
ψo
LqIq
β
d
Id
ψa
Iq = Iocosβ
Id = Iosinβ

Fig. 3



120
100
80
60
40
20
0
-20
-40
-20
0
20
40
60
80
100
Exp.data
Total torque
Magnet torque
Reluctance torque
Torque (T)
Phase of Current (β)

Fig. 4

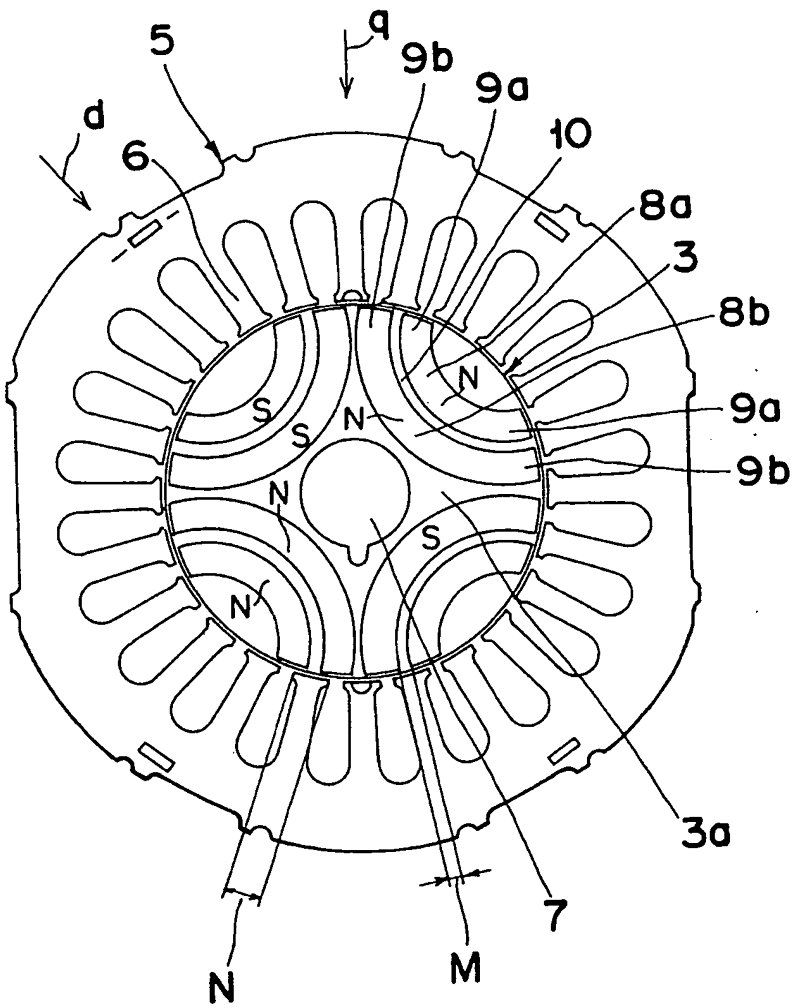


Fig. 5

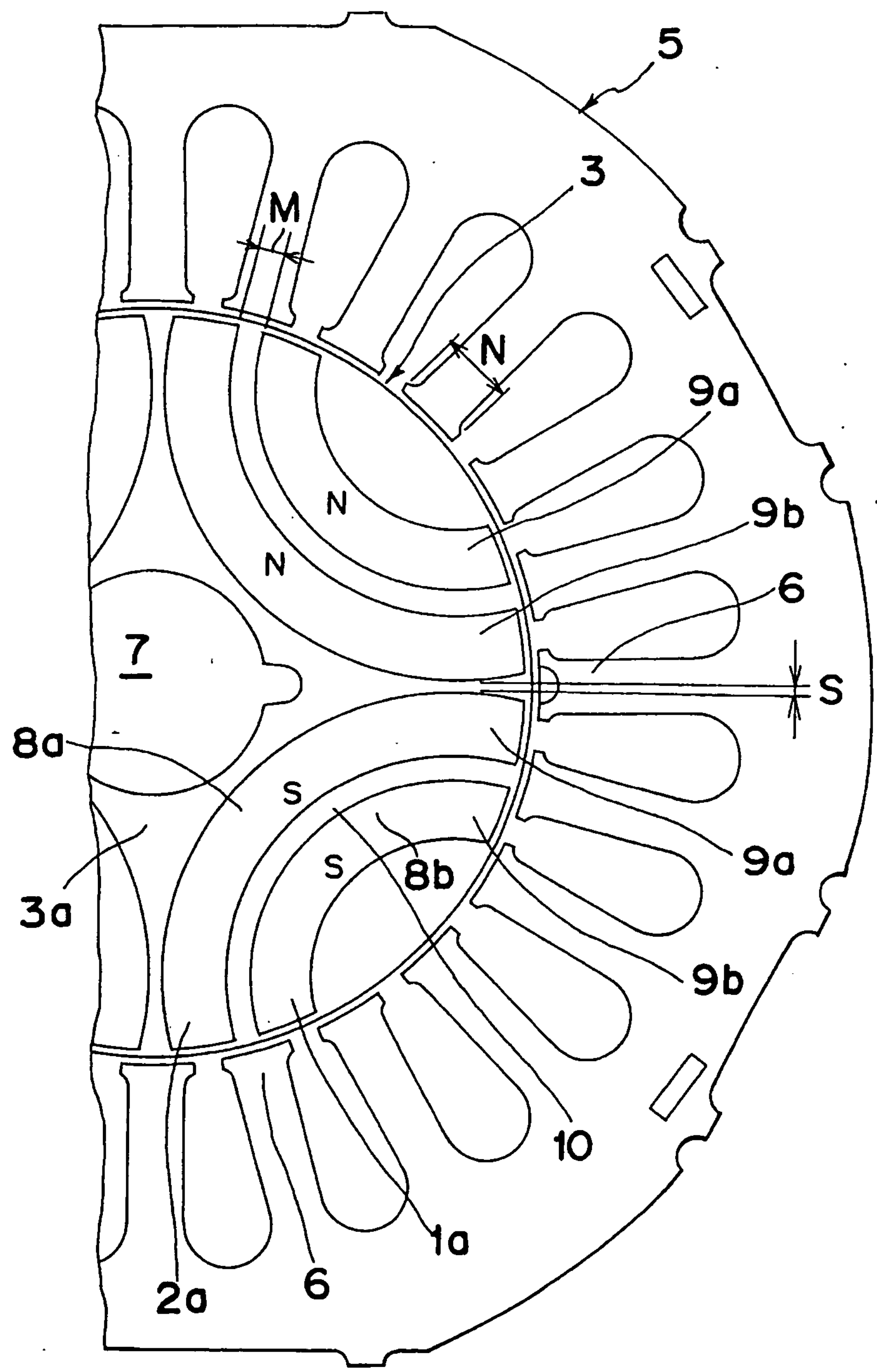


Fig. 6

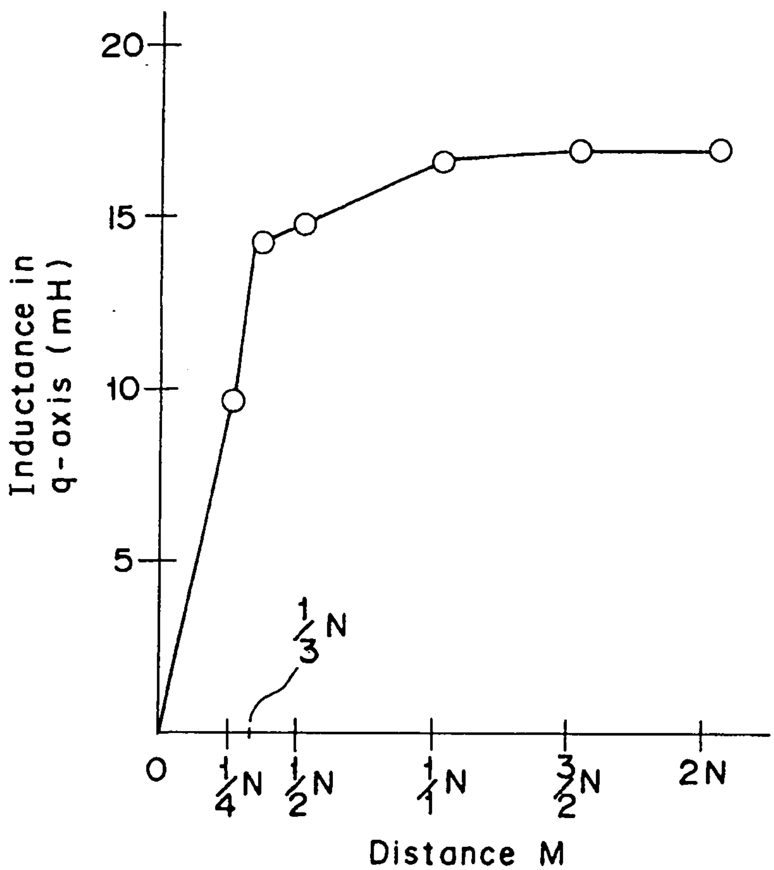

20
15
10
5
Inductance in q-axis (mH)
1/3 N
0
1/4 N
1/2 N
1/1 N
3/2 N
2 N
Distance M

Fig. 7

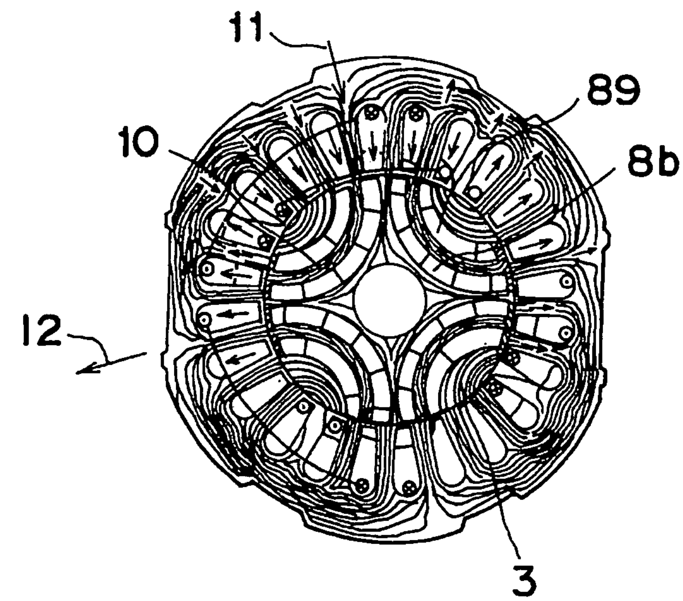


Fig. 8

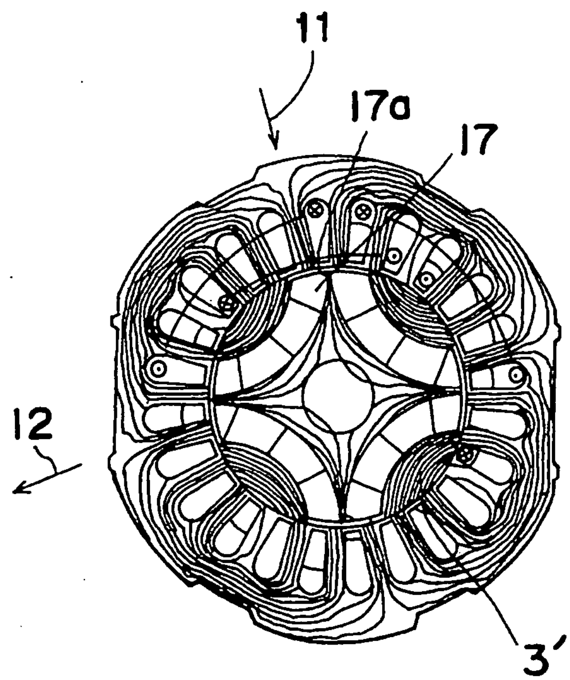


Fig. 9

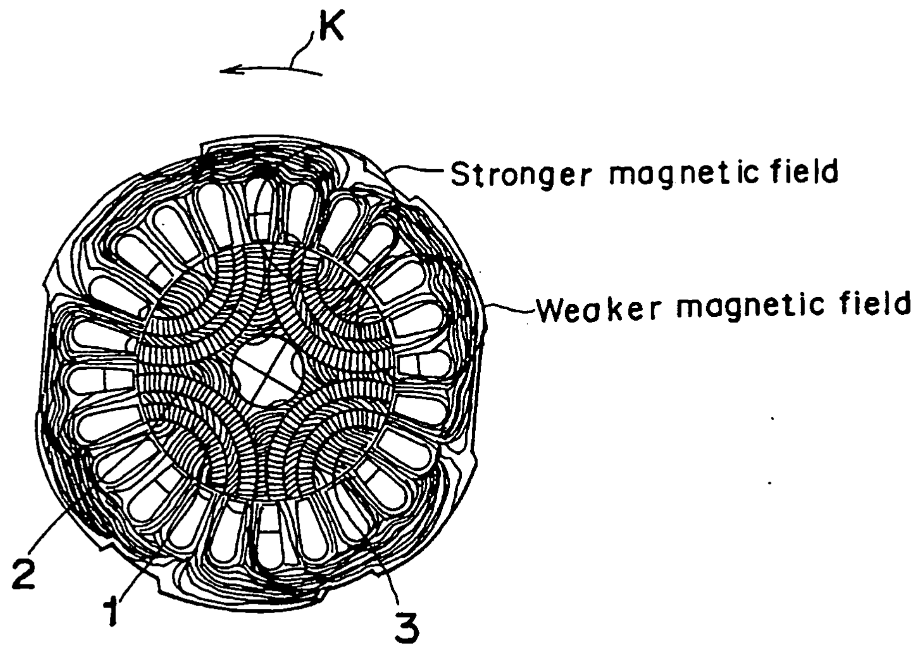


Fig. 10

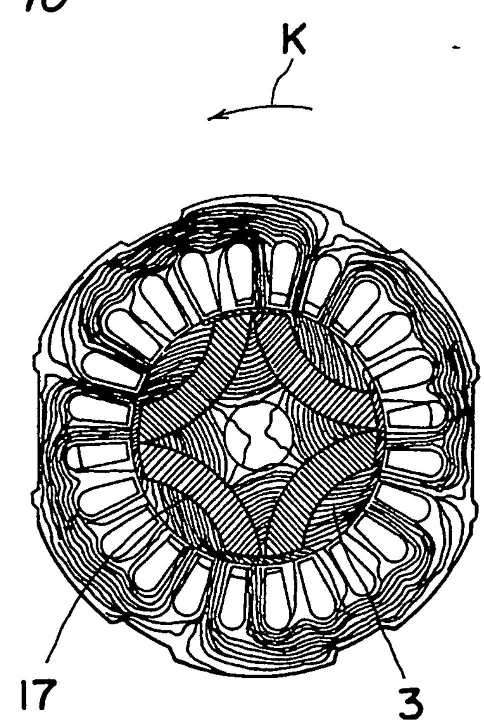


Fig. 11

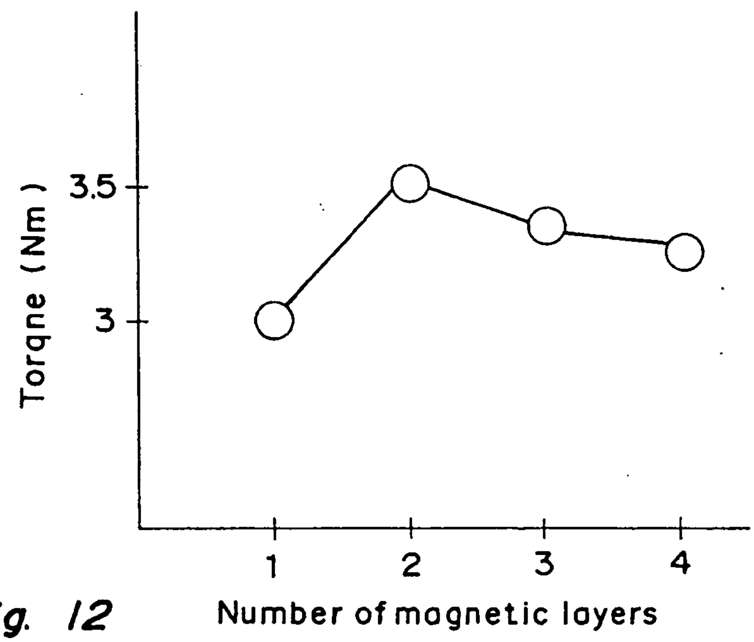

Torqne (Nm)
3.5
3
1
2
3
4
Number of magnetic layers

Fig. 12

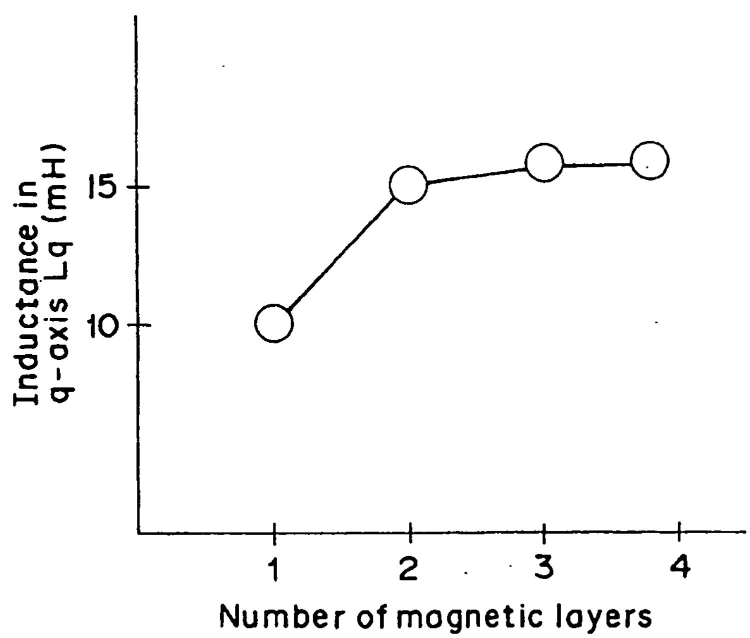

Inductance in q-axis Lq (mH)
15
10
1
2
3
4
Number of magnetic layers

Fig. 13

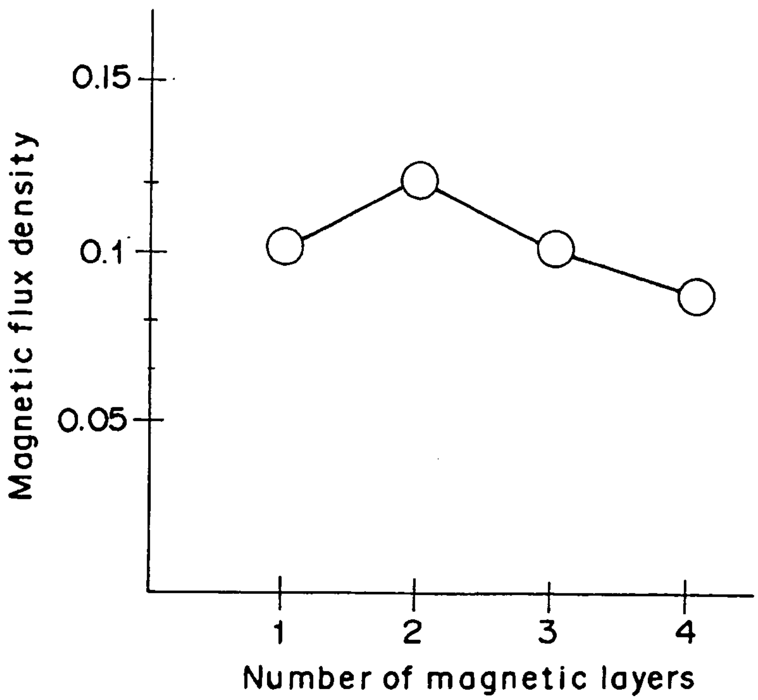

0.15
0.1
0.05
Magnetic flux density
1
2
3
4
Number of magnetic layers

Fig. 14

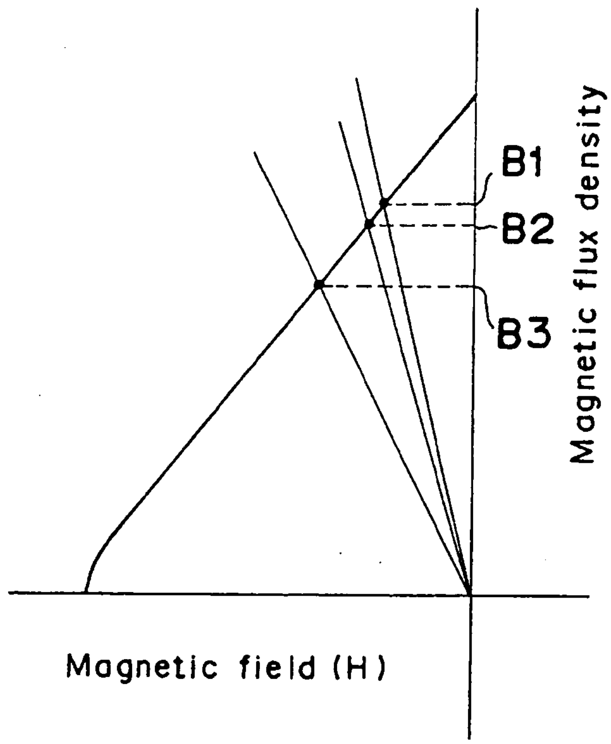


Fig. 15

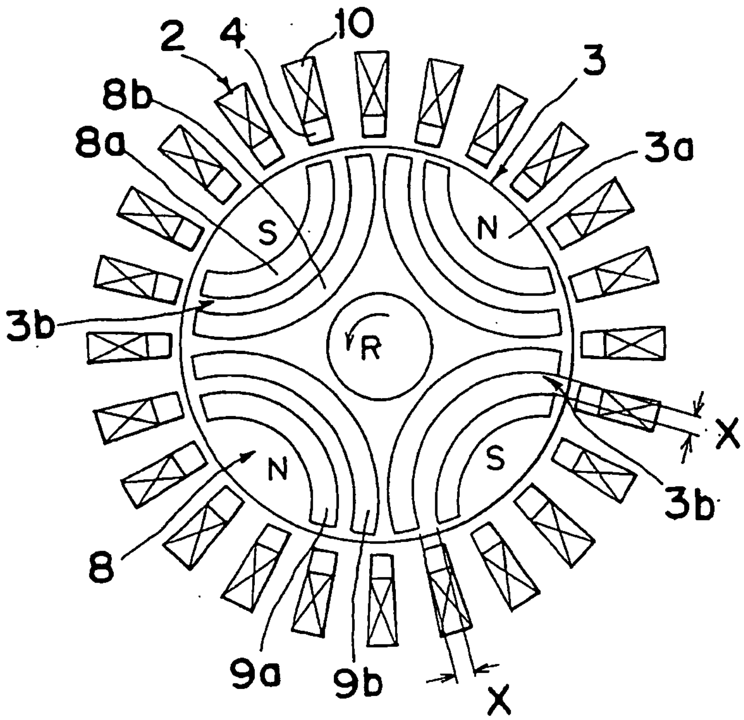

2
4
10
3
8b
8a
3a
S
N
3b
R
X
N
S
3b
8
9a
9b
X

Fig. 21

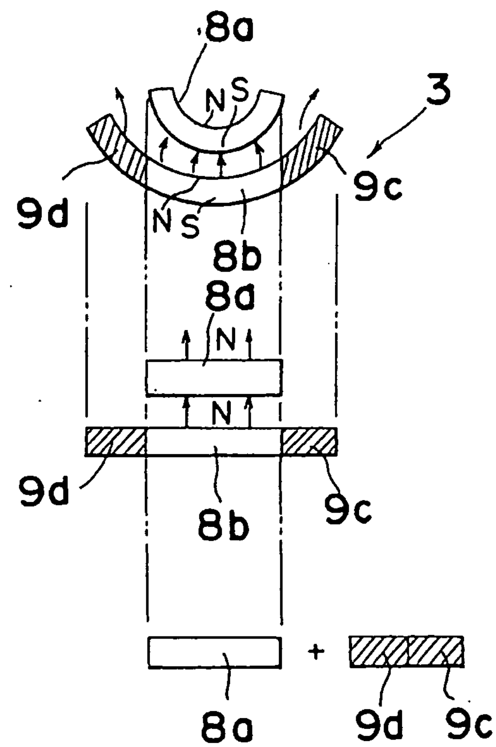

8a
3
N
S
9d
9c
N
S
8b
8a
N
N
9d
8b
9c
+
8a
9d
9c

Fig. 16

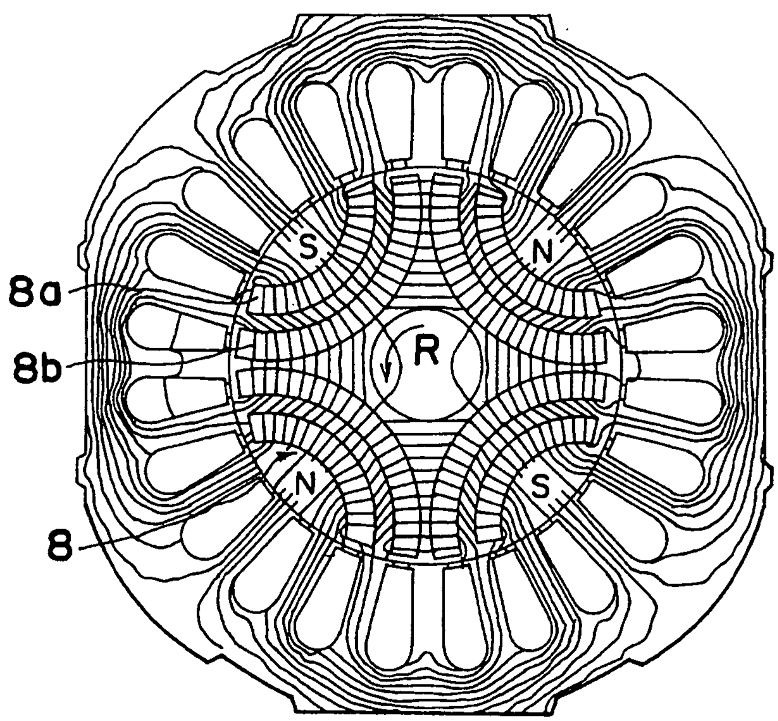


Fig. 17

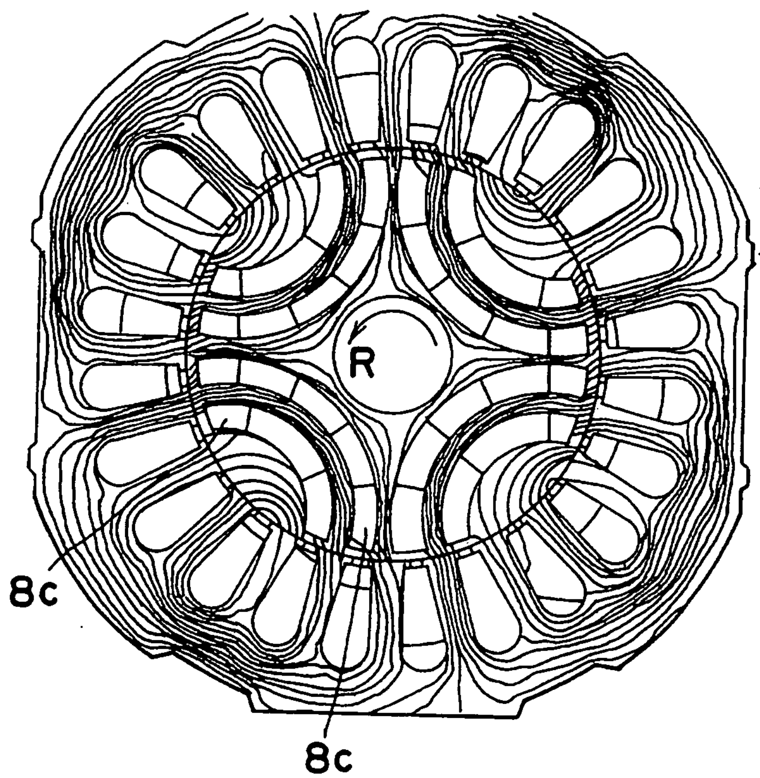


Fig. 18

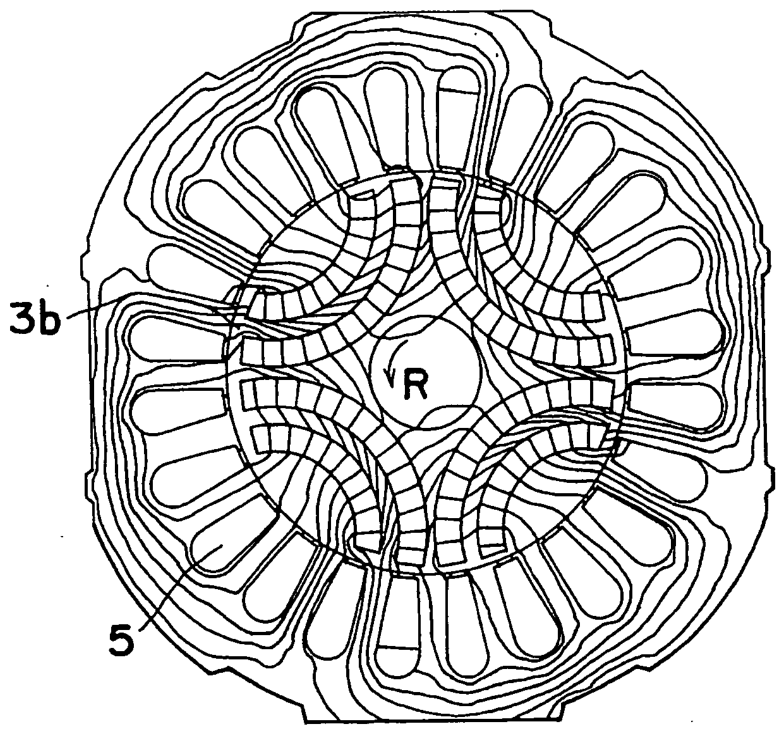


Fig. 19

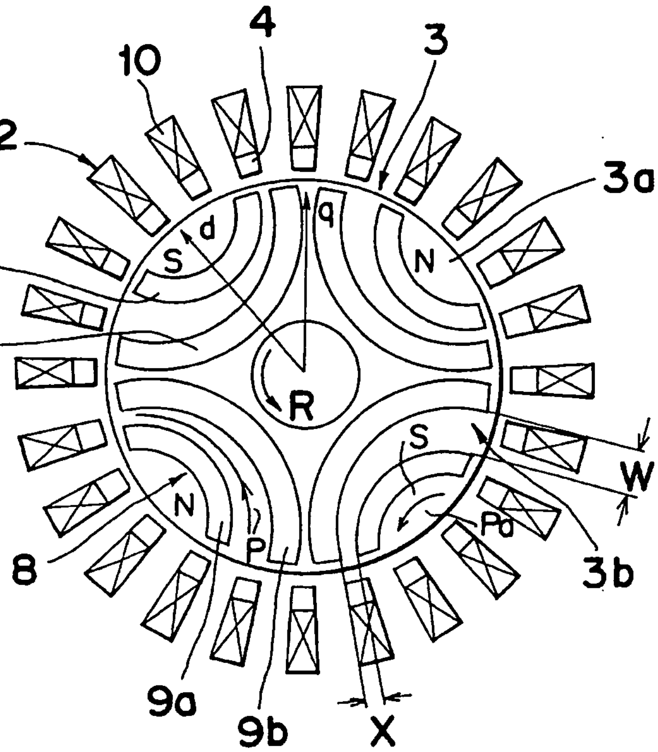

4
3
10
2
3a
d
q
S
N
8a
8b
R
S
W
N
Pa
P
8
3b
9a
9b
X

Fig. 20

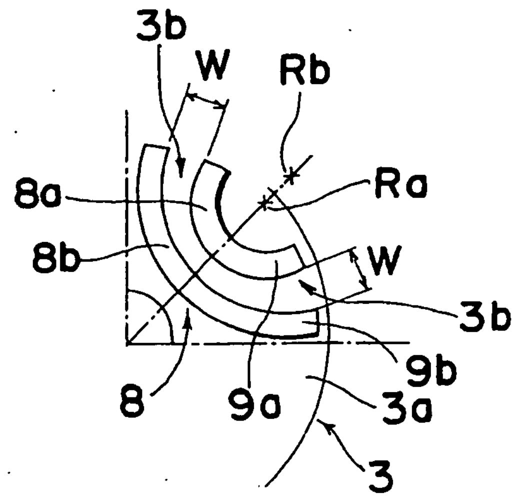

3b
W
Rb
8a
Ra
8b
W
3b
9b
8
9a
3a
3

Fig. 22

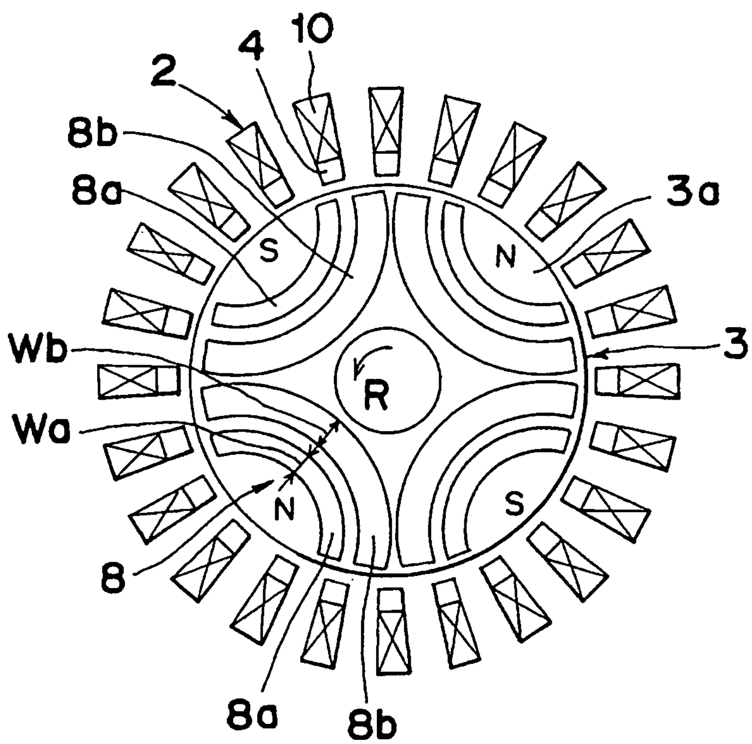


Fig. 23

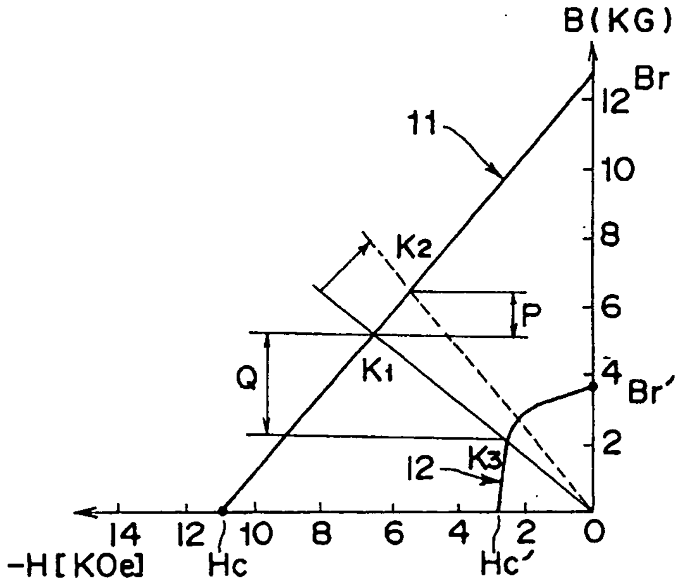


Fig. 24

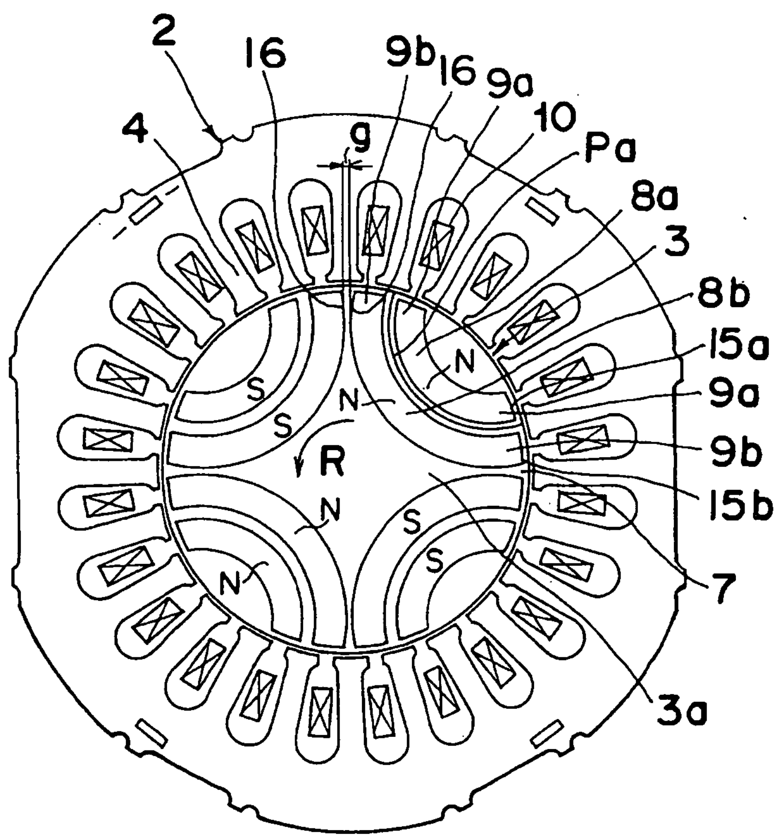


Fig. 25

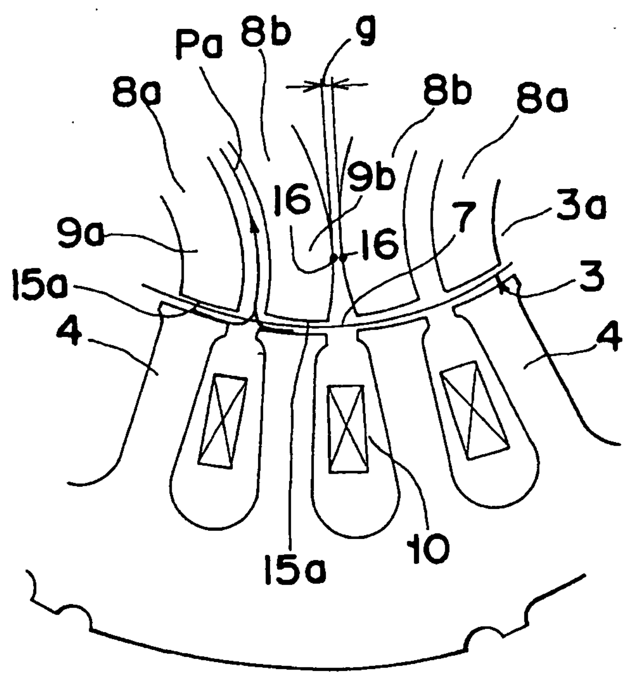


Fig. 26

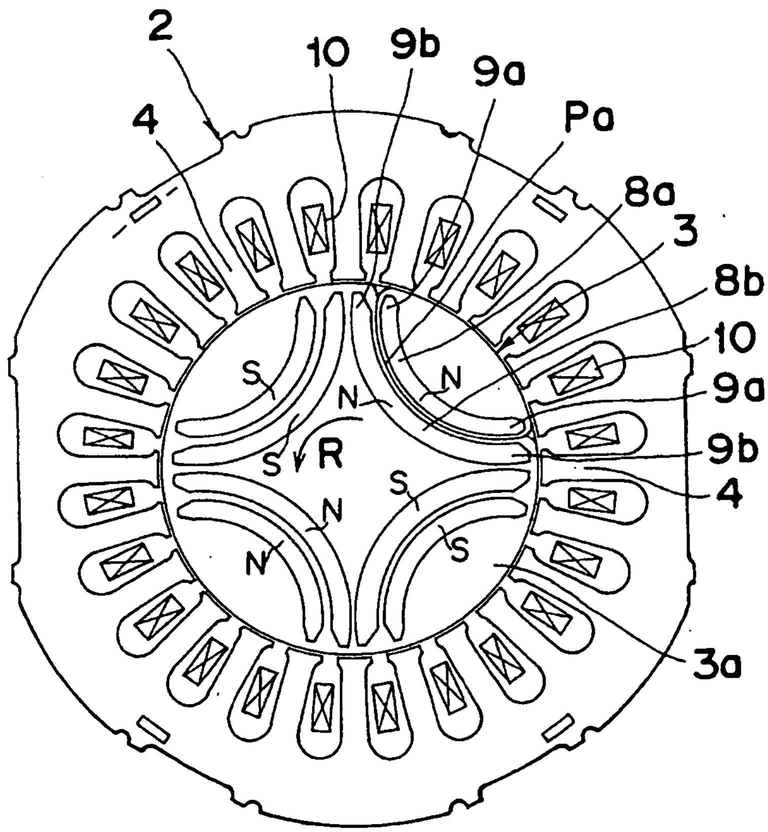


Fig. 27

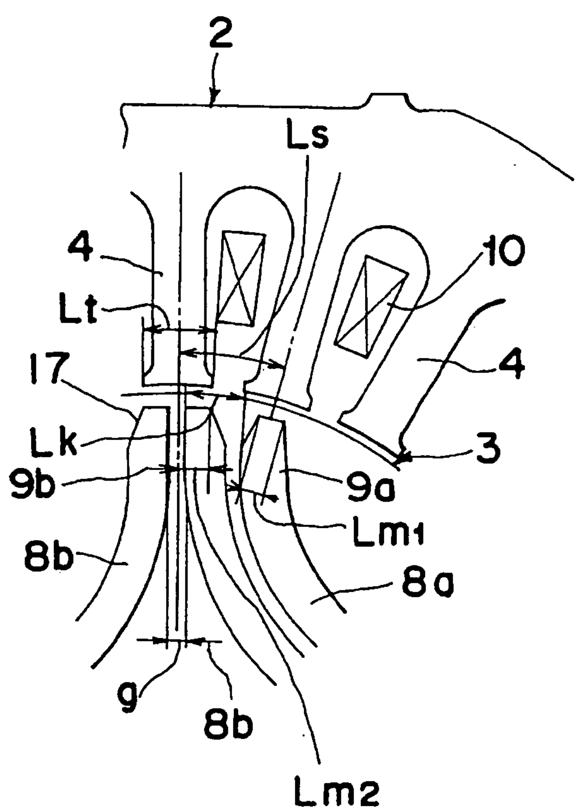


Fig. 28